White Paper

StarRotor Engine:
A Novel Power Source for the Military

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Identification and Significance of the Problem

The military requires power sources for applications including battery recharging, computing, communications, cooling, land vehicles, aircraft (manned and unmanned), ships, directed energy weapons, etc. The ideal properties of the power source follow:

- Efficient
- Power dense
- Low maintenance
- Long life
- Multi-fuel (including standard military fuels)
- Quiet
- Small thermal signature
- Vibration free
- Low cost
- Wide turn-down ratio
- Low emissions

Conventional technologies that have been considered to address this need include the following:

<u>Diesel engines</u> are noisy, dirty, vibrate, and emit an unacceptable thermal signature. Most Diesel engines cannot use a wide range of fuels.

<u>Stirling engines</u> can burn a wide range of fuels, but they have a low power density because they require many heat exchangers.

<u>Fuel cells</u> require hydrogen fuel, which is difficult to make from common battlefield fuels. Also, fuel cells are prone to leak hydrogen – an explosive gas – because it is difficult to seal such a small molecule.

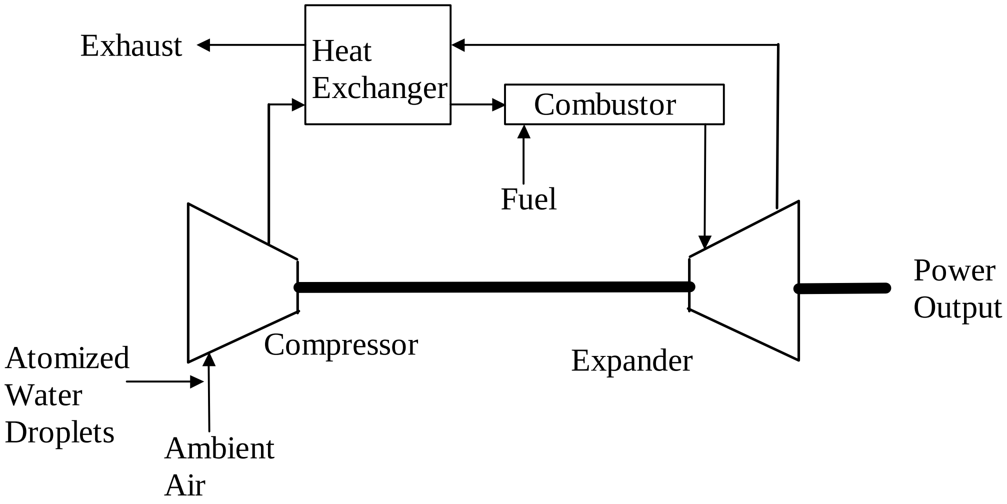
<u>Gas turbines</u> must operate at high speeds, are noisy, and are inefficient when operated off of their design conditions. They also are expensive and require highly filtered air to prevent damage to the spinning blades.

All of the conventional technologies have serious limitations. We propose that the StarRotor engine – a recently patented positive-displacement, rotary Brayton cycle engine – is a superior approach that meets the military's need for power. The StarRotor engine has all of the ideal properties listed above.

Technical Approach

Figure 1 shows a schematic of a Brayton cycle engine. Ambient air is compressed and directed to a recuperator, a countercurrent heat exchanger that preheats the compressed air. The preheated air goes to a combustor where fuel is ignited to obtain the desired expansion temperature. The multi-fuel combustor can be designed to burn any fuel with little pollution. The hot compressed air flows to an expander where thermal energy is converted to shaft work. A portion of the shaft work is invested in the compressor and the remaining portion accomplishes useful work. The hot exhaust gases from the expander are sent to the recuperator where they are cooled and then discharged. Because the exhaust gas is cool, the thermal signature is small.

To improve the efficiency of the Brayton cycle engine, atomized liquid water can be sprayed into the compressor inlet. As the liquid water evaporates during the compression, it keeps the compressed gas cool, which lowers the required compression work. Because the compressor exhaust is cool, it allows the exhaust from the heat exchanger to be cool as well, thereby reducing the thermal signature. (Note: Water spray



is an <u>option</u> that boosts efficiency – it is not essential and can be eliminated when water is scarce.)

Brayton cycle engines have a high power density, which is why they are used to propel jet aircraft. In contrast, Otto and Diesel engines have a lower power density. Further, because Otto and Diesel engines release high-pressure air to the environment, the throttling noise is very loud. In contrast, the Brayton cycle releases the exhaust gas at 1 atm, offering the potential to be quiet, provided mechanical noises are minimized.

The major challenge in implementing Brayton cycle engines is to find a means to process large volumes of air to achieve a desired power output. Traditionally, this is accomplished using dynamic (i.e., axial or centrifugal) compressors and expanders. Unfortunately, these devices require very high speeds – 100,000 rpm for a 30-kW unit sold by Capstone – to develop the desired pressure and flow. Also, they do not have a large “turn-down” ratio, meaning they operate efficiently only at one speed. Further, they are affected by changes in air density, which can result from varying humidity or altitude. Positive displacement compressors and expanders overcome this problem; however, most conventional approaches have severe problems (e.g., low power density, imbalance), making them unacceptable.

StarRotor Engine

The patented StarRotor Brayton cycle engine (U.S. Patent 6,336,317) uses gerotors for both the compressor and expander. (The reviewer is kindly directed to the website StarRotor.com to view animations of the engine.) The gerotor overcomes the problems of common positive displacement compressors and expanders.

The StarRotor compressor (Figure 2) has an inner gerotor with *n* teeth and an outer gerotor with *n* + 1 teeth. (Typically, we use *n* = 5 to 10, but others are possible.) As the gerotors rotate, the void that opens draws air in through the inlet port. As the rotation continues, the void closes and compresses the air. When the air is compressed enough, the compressed air exhausts through the outlet port. The compression ratio is

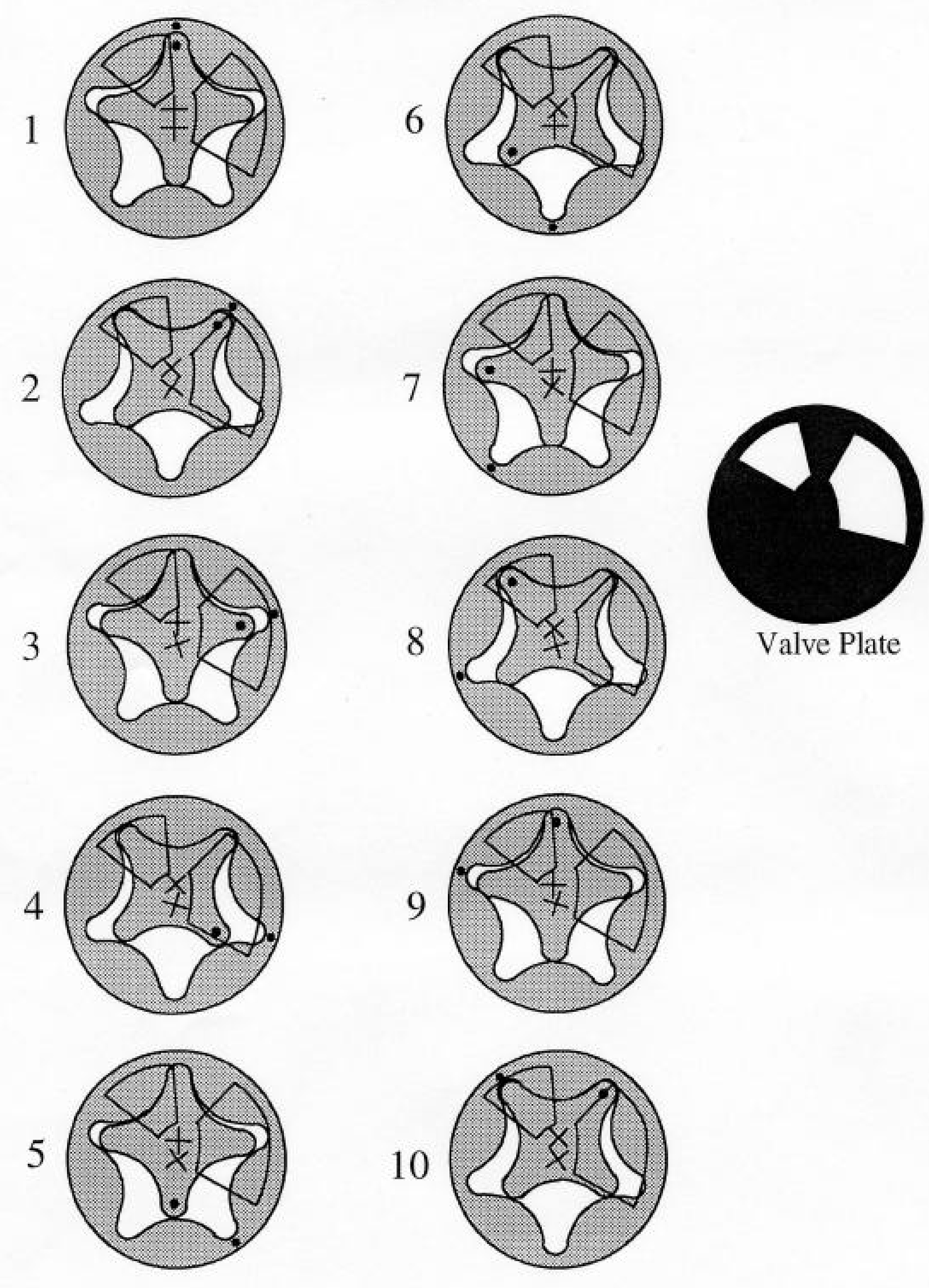


Figure 2. Porting for StarRotor compressor.

determined by the position of the leading edge of the outlet port. Power output from the engine can be regulated by designing the port to have a sliding leading edge, a very energy-efficient method of power control. Because the void opens *n* + 1 times per revolution of the outer gerotor, the gerotor compressor is able to process enormous volumes of gas in a very compact size.

The expander operates similarly to the compressor, except in reverse. High-pressure gas enters through the inlet port, the smaller of the two ports. As the void volume opens, the gas expands doing work on the gerotor. When the pressure reduces to 1 atm, the gas exhausts through the larger port, the exhaust port.

In the Brayton cycle engine, lubricants are not compatible with the high temperatures of the expander, therefore the gerotor teeth must be dry. To prevent wear and friction, there must be no physical contact between the teeth of the inner and outer gerotors. To minimize gas leakage through the small gap, an inexpensive surface treatment is employed. An external synchronization mechanism ensures proper motion of the inner and outer gerotors. Here, there is not sufficient space to describe the synchronization mechanism. The website StarRotor.com provides more details.

Because the inner and outer gerotors do not touch, there is little maintenance required. The life of the engine is expected to be very long because there is little wear. Because there are so few parts, the engine is expected to be reliable.

The engine can be started using a conventional electric starter. Alternatively, it can be started by directing compressed air (stored during the previous operation of the engine) through the expander.

Properties of a StarRotor Engine

Table 1 summarizes the estimated properties of StarRotor engines suitable for the military. The power ranges from 50 W (for powering electronics, such as laptop computers) to 50,000 kW (for powering ships). The low-power engines employ a single stage that compresses air from 1 to 6 atm. The medium-power engines employ a second stage that compresses air from 6 to 36 atm. The high-power engines employ a third stage that compresses air from 36 to 216 atm.

The estimated properties are based upon a few case studies, with scaling laws used to extrapolate to the other engines. In each case, the rotational rate was limited by stresses in the expander outer rotor. It was assumed that the material was silicon carbide embedded with randomly oriented carbon fibers, a material that is available from StarFire Systems.

The power density is improved by using small-diameter rotors that rotate rapidly. Using this design philosophy, the engines have a large aspect ratio (*A*), which is defined as the length-to-diameter ratio. For each engine, the aspect ratio was selected using engineering judgment; in fact, any aspect ratio is theoretically possible. In practice, the engine will be divided into *N* segments, each with a smaller aspect ratio. For example, the 2-stage 50-kW engine has a diameter of 9.6 cm and a length of 91 cm (*A* = 9). The engine could be divided into 7 segments, each with a 13-cm length. Six of the segments would operate as the first stage and one would operate as the second stage.

Depending upon the application, each engine segment could operate independently. For example, each segment could have its own electric generator; the electrical output from all generators would be combined to satisfy the load. Alternatively, the engine segments could be ganged together to drive a common gear with a single output shaft.

In Table 1, the mass and power density of each engine is reported. The general trend is that smaller engines are more power dense. Also, more stages increase the power density. The reported mass includes the compressor and expander, but not the ducting, combustor, or heat exchangers.

For comparison purposes, Table 2 shows the power densities of conventional engines. Based upon power density, the StarRotor engine compares well with all engine types except large gas turbines. Of course, the high turn-down ratio of the StarRotor engine may make it appealing even for applications that currently use large gas turbines.

Table 1. Properties of StarRotor Engines

1-Stage							
P [kW]	Eff. [%]	D [cm]	L [cm]	A	RPM	m [kg]	P/m [kW/kg]
0.05	17	1.25	5.0	4	100,000	0.022	2.3
0.5	28	2.4	9.8	4	84,000	0.153	3.3
5	40	6.3	25.7	4	32,800	2.77	1.8
50	44	10.6	137	13	20,000	41.6	1.2
500	47	31.8	413	13	6,800	1,136	0.4
5,000	52	74	1,560	21	2,950	23,530	0.2
50,000	57	168	6,240	37	1,340	478,800	0.1

2-Stage							
P [kW]	Eff. [%]	D [cm]	L [cm]	A	RPM	m [kg]	P/m [kW/kg]
50	44	9.6	91	9	21,800	22	2.3
500	47	20	425	21	10,750	452	1.1
5,000	52	45	1,820	40	4,750	10,288	0.5
50,000	57	120	4,250	29	1,550	239,404	0.2

3-Stage							
P [kW]	Eff. [%]	D [cm]	L [cm]	A	RPM	m [kg]	P/m [kW/kg]
5,000	52	36	1,210	33	6,000	4,267	1.2
50,000	57	80	4,409	46	2,300	110,491	0.46

Table 2. Properties of Conventional Engines

Make/Model	Power [kW]	Mass [kg]	Power Density [kW/kg]
AIRCRAFT ENGINES (PISTON)			
Avco Lycoming/I0-360-A	149	132.6	1.12
Avco Lycoming/TIGO-541-E	317	316.8	1.00
Teledyne Continental 0-200	75	86	0.87
OUTBOARD ENGINES (PISTON)			
Evinrude Yachtwin 6	4.5	25.5	0.18
Mercury 200	149	165	0.90
GAS TURBINES (MECH. DRIVE)			
Rolls-Royce Avon 2648	15,180	15,875	0.96
GE PGT25	23,261	34,475	0.67
DIESEL ENGINES			
Caterpillar 3618	7,200	37,500	0.19
Caterpillar C9	375	947	0.40

StarRotor Development Team

Dr. Mark Holtzapple, President of StarRotor Corporation and Professor of Chemical Engineering at Texas A&M University, heads the StarRotor development team. He has a long history of working with engines. From 1982 to 1985, while serving as a captain in the US Army at Natick R, D, and E Center, he helped develop a miniature Stirling engine for cooling soldiers encapsulated in chemical protective clothing.

Dr. Kyle Ross is a chemical engineer with a PhD from Texas A&M University. He has broad expertise ranging from software development, materials, and mechanical design.

Andrew Rabroker is a mechanical engineer with an MS from Texas A&M University. Soon, he will complete his PhD. He has a wide range of skills including machine design, stress analysis, materials, machining, and welding.

Tom Beck is a mechanical engineer with an MS from the University of Alabama. In addition, he is rated as a Master Tool and Die Maker, the highest rank among machinists. He focuses on converting design concepts into working hardware.

Facilities

StarRotor Corporation has a 3,200-ft^2 shop equipped with a temperature-controlled room that houses a Hass VF-5 mill. The mill can machine parts up to 5 ft × 2 ft × 1.5 ft. It is accurate to 0.0002 in and reproducible to 0.0001 in. The mill has a wide variety of cutting tools, measuring equipment, and calibration equipment. In addition, we have metal cutting tools, drills, welders, plasma cutters, and a band saw.

We have six workstation computers. Commercial software includes Inventor (3-D solid modeling), Algor (FEA analysis of stress, deflection, heat transfer, and fluid flow), FeatureCAM (computer-aided manufacturing), and Microsoft Office. In addition, we have written custom software that determines gerotor geometry, efficiency, and bearing loads.

We have a 100-kW, 10,000-rpm, variable-speed electric motor that can be used to drive compressors. It is computer-controlled through LabWindows software. We have numerous sensors, including speed, torque, temperature, pressure, vibration, and mass flow. The collected data are analyzed and stored on the computer.

Past Accomplishments

The StarRotor development team has constructed a 75-kW StarRotor compressor that has already undergone the first phase of testing. The second phase of testing should begin in April 2004.

A 500-W face-breathing StarRotor compressor has been constructed and undergone the first phase of testing. It is about 11 cm in diameter and about 11 cm long.

A 500-W tip-breathing StarRotor compressor has been designed; construction should be completed in May 2004. It is about 4 cm in diameter and 5 cm long.

Numerous proprietary software packages have been developed to help design StarRotor compressors and expanders.

Design studies have been performed for complete engines (compressor + expander), but a detailed design has not yet been performed for an engine.

Proposed Research

We propose to design, build, and test a 20-kW, single-stage engine. These tasks should require approximately 2 years to complete and cost about $1 to 2 million.

Conclusion

The StarRotor engine is a new development that has been recently patented. It can be constructed at a wide range of scales, from 50 W to 50,000 kW. It offers the following benefits to the military: high efficiency, high power density, multi-fuel, low noise, low vibration, low pollution, low maintenance, long life, low thermal signature, and wide turn-down ratio.